An investigation of indoor air quality, thermal comfort and SBS symptoms in UK energy efficient homes: A case study

Abstract

Purpose - Awareness of the deterioration of indoor air quality as a result of energy efficient building design strategies is growing. Apprehensions of the effect of airtight, super insulated envelopes, the reduction of ventilation rates, and the reliance on mechanical systems to provide adequate air supply is promoting emerging new research in this field. This paper discusses recent findings and presents results of an indoor air quality and thermal comfort investigation in UK energy efficient homes, through a case study investigation.

Design/Methodology/Approach – The case study dwellings consisted of a row of six new build homes which utilize mechanical ventilation with heat recovery (MVHR) systems, are built to an average air tightness of $2m^3/m^2/hr$ @ 50 Pascal's, and constructed without a central heating system. Physical indoor air quality measurements and occupant interviews were conducted during the summer and winter months over a 24 hour period, to gain information on occupant activities, perception of the interior environment, building related health and building use.

Findings – The results suggest inadequate indoor air quality and perceived thermal comfort, insufficient use of purge ventilation, presence of fungal growth, significant variances in heating patterns, occurrence of Sick Building Syndrome (SBS) symptoms and issues with the MVHR system.

Practical Implications – The findings will provide relevant data on the applicability of air-tight, mechanically ventilated homes in a UK climate, with particular reference to indoor air quality.

Originality/Value – Indoor air quality (IAQ) data of this nature is essentially lacking, particularly in the UK context. The findings will aid the development of effective sustainable building design that is appropriate to localized climatic conditions and sensitive to the health of building occupants.

Keywords: Indoor air quality; Energy Efficiency; Sick Building Syndrome (SBS) Symptoms, Thermal Comfort; Case Study; UK

1. Introduction

Household energy use accounts for over a quarter of the total energy consumption and subsequent carbon dioxide emissions in the UK (Palmer et al. 2011). Through the introduction of the Climate Change Act (HM Government 2008), a legally binding target of an 80% reduction in carbon emissions by 2050 from 1990 figures has been established by the UK parliament (DEFRA 2007). As a result, there has been a significant drive towards low energy and/or energy efficient housing designs and refurbishment strategies. Rigorous changes to UK building regulations require all new dwellings to achieve a maximum permissible air permeability of 10m3/(h.m2) @50Pa, Target Emission Rates (TER), and maximum U-values for building elements (DFPNI (Department of Finance and Personnel NI) 2012). Mandatory airtightness tests are therefore necessary for all (or samples of) new build UK dwellings (Energy Saving Trust 2007, Jaggs, Scivyer 2009). In response however, modern buildings are significantly exceeding airtightness standards legislated by UK building regulations, with achievable air airtightness values of 3-4m3/(h.m2) @50Pa utilizing standard methods of construction (Yu, Kim 2012).

Emphasis on airtightness and fabric efficiency is likely to increase, given the UK target of zero carbon new build homes by 2016 (Zero carbon hub, NHBC 2013). The consequences of these design strategies on the quality of the indoor environment however are generally unknown. As suggested by the Innovation and Growth Team (2010), there is a "worrying absence of skills regarding indoor air quality in low carbon buildings", which "should be addressed as a priority". This is supported by VIAQ Task Group (Sullivan et al. 2012), who state further evidence on the effect of MVHR on IAQ in homes is required as a matter of urgently.

Post occupancy evaluations and IAQ assessments in energy efficient homes remains disturbingly low. The limited research that is available suggests significant problems with reduced ventilation rates in the home environment. For instance, in a multidisciplinary review of the scientific literature, Sundell et al. (2011) identified an association between ventilation rates above 0.5 ach (air changes per hour) and reduced risk of allergic manifestations in a Nordic climate among children. This is supported by Gilbert et al. (2008) who explain reduced air changes may significantly increase the concentration of pollutants such as formaldehyde in homes, since most sources originate indoors.

In Europe, a review by Dimitroupoulou (2012) found dwelling ventilation rates in practice were often insufficient (<0.5h-1), resulting in increased pollutant exposure and adverse health effects. As suggested by Offermann (2009), energy efficient building practices and standards have resulted in a reliance on appropriate occupant engagement to ensure adequate ventilation. However as stated by Clausen et al. (2003), poor building operation such as reducing ventilation for energy conservation is common, and may result in significant deterioration of the indoor environment.

A further problem arises with the increased air tightening of building envelopes, which reduces natural ventilation through infiltration and may potentially lead to problems with 'back-drafting' of combustion appliances (Nazaroff 2013). As suggested by Wal et al. (1991), increasing dwelling airtightness subsequently leads to increased concentration of indoor air pollutants. This is supported by BRE (2006), who explain, "As dwellings are made more airtight, internal pollutant sources can have a greater impact on indoor air quality and occupants may experience adverse health effects unless ventilation is effective". As suggested by Stellman (1998), prevalent features of Sick Building Syndrome (SBS) cases are buildings of energy efficient, modern design or recently retrofitted buildings. This is supported by Molina et al. (1989) who state, "Insufficient ventilation due to energy saving measures following the oil crisis has been claimed as one of the main causes for SBS symptoms". This is reflected in the UK NHBC report (Davis, Harvey 2008), which states 76% of homeowners interviewed were put off by the levels of airtightness in highly energy efficient homes because of apprehensions on restrictions to ventilation and/or fresh air.

In the UK, the use of mechanical ventilation strategies (particularly MVHR) is virtually standard in new build energy efficient dwellings (NHBC 2009). If installed and operated correctly, MVHR has the potential to improve IAQ by reducing exposure to dust mite allergens (Eick, Richardson 2011), particles through filtration (Bone et al. 2010) and air pollutants through provision of fresh air and climate control (Mardiana-Idayu, Riffat 2012). Recent research however suggests short-comings of MVHR systems, particularly in the UK climate. For instance, a study by Sullivan et al. (2012) highlights issues with maintenance access, low standards of installation, lack of competently trained individuals, insufficient operation and poor commissioning.

This is supported by Turner et al. (2013), who explain, "Deficiencies occur because systems are field assembled (usually without design specifications), there is no consistent process to identify and correct problems, and the value of such activities in terms of reducing energy use and improving IAQ is unknown". Furthermore, a report by Clausen et al. (2003) identifies the following risks with mechanical ventilation systems; "HVAC-components may be dirty when installed or become dirty and release pollutants and odours; poor control of indoor temperature due to absence of cooling; low humidity in winter; noise generated by forced air flow and fans; draft caused by forced air flows".

As suggested by Sullivan et al. (2012), "The current trend towards mechanical ventilation with heat recovery (MVHR) will continue and it is likely to become the dominant form of ventilation in new homes". It is therefore fundamental that, to ensure occupant health is not adversely affected in the process of energy conservation, more research investigating the effects of these new technologies and strategies are employed.

The objective of this study thus is to investigate the effects of energy efficient building design strategies on the indoor air quality, perceived environmental quality and health/wellbeing of building occupants. A case study approach was adopted in a UK context, through employment of physical indoor/outdoor air quality measurements, available energy data and building information, occupant interviews, activity diary, weather monitoring and building survey. Ventilation was also discussed, with particular reference to the use of MVHR. The findings may be used to support the growing body of knowledge on IAQ in energy efficient homes, including recommendations and future research needs.

2. Household Characteristics

This study investigated the IAQ of a row of six airtight, energy efficient case study homes located in the UK. The homes (approximately 1,100sq/f) consist of three bedrooms, open plan living room/kitchen and two bathrooms. The construction is based on a standard timber frame with brick outer leaf. The homes are two storied owner occupied with off street parking, and are located in a residential area of moderate population and traffic flow. Mechanical Ventilation with Heat Recovery systems (MVHR) are used in all homes, with a specified efficiency of >80%. The homes are highly insulated with triple glazed windows (U-value of 1.0 W/m^{2}K) and achieve an average air tightness of 2m^3/h/m^2 @ 50 Pa. Solar panels are utilized for hot water demands, in combination with a small air source heat pump for use during the winter months. The homes are compliant with Code for Sustainable Homes level 4 however are equivalent to level 5 in relation to energy use and thermal efficiency. Annual space heating demand is 9.03 Kwh/(m^{2}a). The roof and floors have a specified U-value of 0.11 W/m^{2}K and the walls a U-value of 0.125 W/m^{2}K.

Table 1. Household characteristics

House No.	No. of occupants	No. of smokers	Are cigarettes smoked indoors	Main cooking fuel	Main heating fuel
No.1	3	2	No	Natural gas	Natural gas (fire)
No.2	3	0	N/A	Electric	Natural gas (fire)
No.3	4	0	N/A	Natural gas	Natural gas (fire)
No.4	3	1	No	Electric	Electric (fire)
No.5	2	0	N/A	Electric	Electric (fire)
No.6	5	2	No	Electric	Natural gas (fire)

3. Materials and Methods

The field work was performed during the winter season (between February and March 2013); and summer season (between August and September 2013; May 2014) two to three years after construction work was completed. Occupants were approached by letter and follow up visit to explain the study and monitoring procedure. Occupant interviews were conducted before or after the 24 hour monitoring period.

3.1. Indoor air quality measurements

Monitored IAQ parameters include temperature, relative humidity, carbon dioxide in the open plan living room and kitchen using Extech EasyView model EA80 (relative humidity: resolution 0.1%RH, accuracy ±3-5%RH, temperature: resolution 0.1°C, accuracy ±0.5°C, carbon dioxide: resolution 1ppm, accuracy ±3% or ±50ppm). Temperature, relative humidity and carbon dioxide were also monitored outside and in the bedroom using Wohler CO_2 data-logger (CDL 210- temperature: resolution 0.1°C, accuracy ±0.6 °C, relative humidity: resolution 0.1%, accuracy ±3-5%; carbon dioxide: resolution 1ppm, accuracy ±5% or ±50ppm). Formaldehyde was monitored in the open plan living room and kitchen with a handheld formaldehyde meter (HalTech: HAL-HFX205, resolution 0.01ppm, accuracy ±2%).

Sampling instruments were located in the downstairs living space (open plan living room and kitchen), at breathing height with accordance to ISO 16000 and at least 1m from walls or sources of pollutants. Sampling was conducted for a 24 hour period during a typical weekday. Outdoor measurements of temperature (ºC), relative humidity (%), rain fall (mm), light (lux), wind speed (km/h), wind direction, and absolute pressure (hPa) were monitored simultaneously through use of a weather station (Easy Weather Plus).

3.2. Diary of activities

Occupants were presented with a brief record sheet which they were asked to complete during the measurement period. This was condensed to a single A4 page (for each measurement day), to reduce the burden on the occupants and increase the response rate. The occupant diary included important information on occupancy rates, use of heating, use of air polluting products, window/external door opening and further activities that may have affected the measurement results. The diary required an average input for every hour, for instance average occupancy in measurement room every hour.

3.3. Occupant Interviews

Structured interviews were conducted with occupants through the utilization of various questionnaires; one for each dwelling, one for each occupant, a condensed questionnaire for each child (completed by parent or guardian) and a building survey form. An interview format was adopted to provide the opportunity for further discussion of particular topics and in most cases the interviews were recorded with use of a dictaphone.

The dwelling questionnaire gathered information on building use, occupant activities, the interior environment and general building information. Occupant questionnaires provided details of perceived indoor air quality and thermal comfort, building related illnesses and sick building symptoms utilizing validated procedures (Raw et al. 1995, Berry, R.W., Brown, V.M., Coward, S.K.D., Crump, D.R., Gavin, M., Grimes, C.P., Higham, D.F., Hull, A.V., Hunter, C.A., Jeffery, I.G., Lea, R.G., Llewellyn, J.W. & Raw, G.J. 1996, Burge, Robertson & Hedge 1990, Burge, Robertson & Hedge 1993). A condensed version was employed to gain information on building related health of children. The building survey was completed by the researcher, which included information on building features and general observations.

4. Results

4.1. Ventilation Strategies

During the interview process, occupants were asked how often they used various ventilation strategies during the winter months; the results are presented in Figure 1. As illustrated, five out of six homes never or rarely used the boost mode function. One household explained the ventilation system was noisy on higher settings; another stated they do not touch the system. One household reported using the boost mode only when there was a crowd of people in. Only one home reported opening the windows on a regular basis during winter (in morning), while in five out of six homes the windows were never or rarely open during the evening and/or night. In house No.4 and No.5, the windows in the main bathroom were not operable; the MVHR system was the only available ventilation strategy. When asked whether the boost mode was ever used during showering or bathing, the response was never for five out of six households. These results suggest inadequate use of purge ventilation to rapidly dilute air pollutants and excess water vapor in the case study homes.

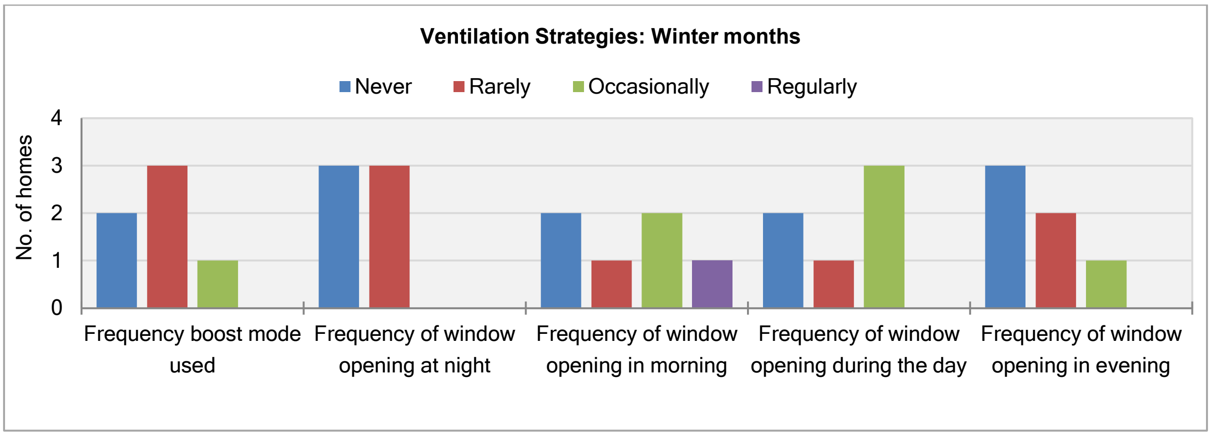

Figure 1. Frequency of ventilation strategies utilized in case study homes during the winter months.

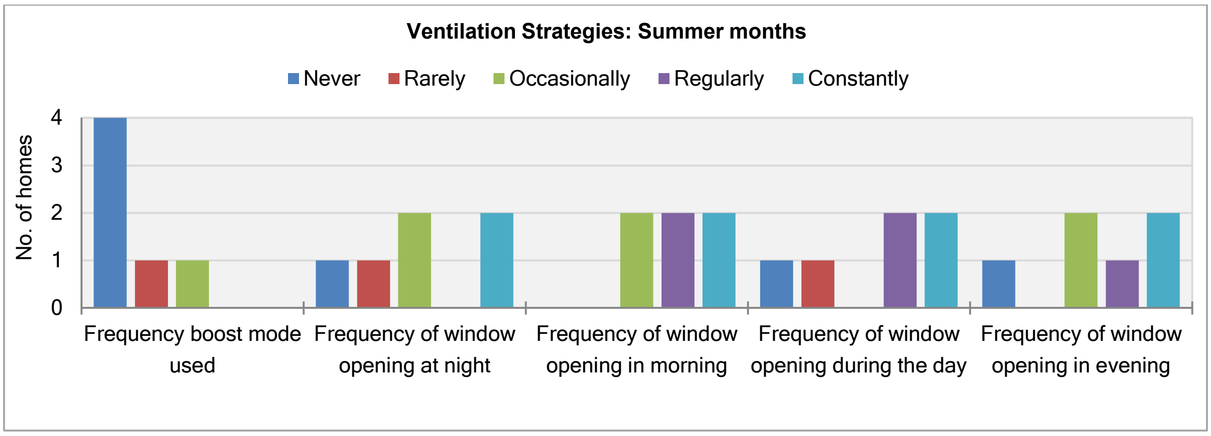

Figure 2. Frequency of ventilation strategies utilized in case study homes during the summer months.

During the summer months, four households stated the boost mode in the MVHR system was 'never' used. The remaining households stated it was occasionally used "when visitors were in", or rarely used "when it is really warm". Two households (No.5 and No.6) stated that windows were opened constantly during summer; in the morning, during the day, in the evening and at night.

All households stated that they found the MVHR (Mechanical Ventilation with Heat Recovery) system easy to operate. Two households (No.3 and No.5) however pointed out that they had adjusted the vents for thermal comfort during winter, explaining they were experiencing draughts from the supply vents. Household No.3 explained that every winter they screw the supply vents slightly closed and open them again during the summer season. Similarly, No.5 explained that during the winter they tighten the bedroom and living room supply vents. This may have had a significant effect on the air change rate, potentially limiting ventilation to inadequate levels.

In the structured occupant interview, three households stated that they have experienced issues with at least one of the following aspects of the MVHR system: noise, cost of running, thermal comfort, draughts or other. Two stated noise as an issue, explaining it is noisy on higher settings and noisy in the bathroom. One household stated cost of running and thermal comfort as issues, explaining that it was "not efficient to heat the house" and "in winter it gets too cold". Thus poor understanding and/or satisfaction with the mechanical ventilation with heat recovery system appears to be a problem in the case study dwellings.

4.2. Carbon dioxide

4.2.3. Winter season

Table 2. Winter carbon dioxide levels (ppm) in living room and average occupancy

	No.1	No.2	No.3	No.4	No.5	No.6
Maximum	2294	1571	2163	920	2106	1566
Minimum	545	470	649	379	584	444
Standard deviation	177.7	392.4	351.7	116.2	311.0	277.4
Average	821.9	984.4	1172.7	579.5	909.5	1021.2
Mean occupancy in living room	0.86	1.81	1.36	1.29	0.77	1.59
Mean occupancy in home	2.14	3.00	2.59	1.81	0.82	2.73

Significantly high peak carbon dioxide levels were recorded (>2,000ppm) in the living room of three of the case study homes; with average carbon dioxide levels over the 24 hour period above 1,000ppm in two homes. Only one home maintained carbon dioxide levels below 1,000ppm during the measurement period. As stated by EPA (Agle, Galbraith 1991), "peak CO2 concentrations above 1000ppm in the breathing zone indicate ventilation problems". This is supported by German Working Group on Indoor Guideline Values of the Federal Environmental Agency and the State's Health Authority (2008), who concluded "based on health and hygiene considerations: concentrations of indoor carbon dioxide levels above 1000ppm are regarded as harmless, those between 1000 and 2000ppm as elevated and those above 2000ppm as unacceptable".

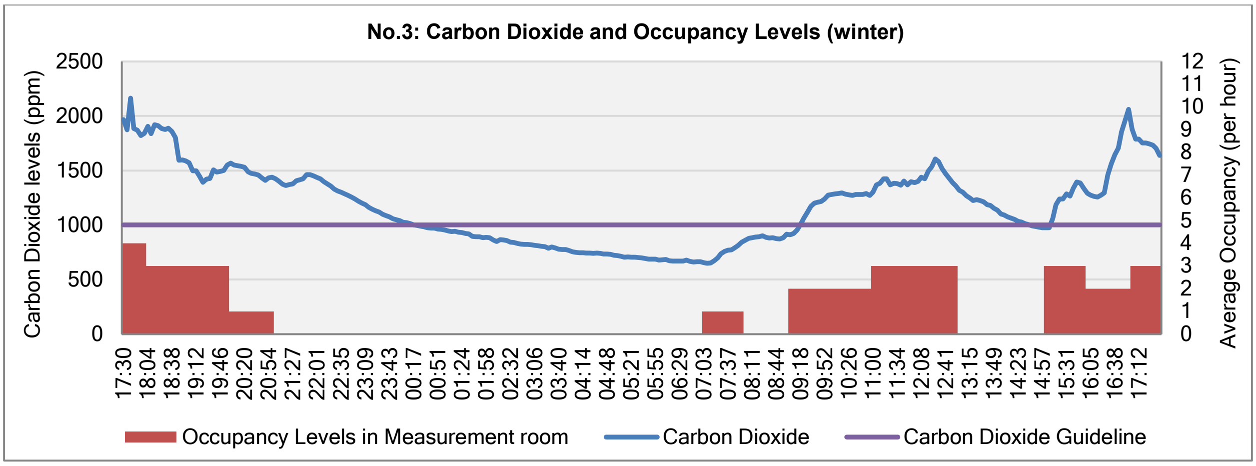

Figure 3. Carbon dioxide and occupancy levels in house No.3 during the measurement period

Typical outdoor concentrations of carbon dioxide range from 350 to 450ppm depending on proximity to outdoor sources, time of day and location (Seppänen, Fisk 2004). ASHRAE's recommendations for indoor carbon dioxide levels are established on outdoor concentrations, stating "maintaining a steady-state CO_2 concentration in a space no greater than about 700ppm above outdoor levels will indicate that a substantial majority of visitors entering a space will be satisfied with respect to human bioeffluents (body odor)" (ASHRAE 2010).

As shown in Figure 3, carbon dioxide levels significantly correlated with average occupancy levels (as recorded through use of occupant diary), during the measurement period. It should be noted that house No. 3 has four occupants, and during the period where four people were in the open plan living room and kitchen (between 17:30-18:00), the carbon dioxide levels peaked at 2163 ppm. This suggests the MVHR system is not capable of coping with every-day occupancy. This may be as a result of occupants adjusting the supply vents, poor commissioning, and/or faults with the MVHR system.

4.2.4. Summer season

Table 3. Summer carbon dioxide levels (ppm) in living room

	No.1	No.2	No.3	No.4	No.5	No.6
Maximum	1074	1126	781	1100	1347	1034
Minimum	488	530	453	402	446	537
Standard deviation	156.4	162.4	65.9	194.9	234.6	98.2
Average	760.2	762.7	523.3	669.1	723.9	693.7
Mean occupancy in living room	1.08	1.12	0.28	0.75	1.20	1.13
Mean occupancy in home	2.17	2.56	0.64	2.50	1.84	2.13

During the summer months carbon dioxide levels were lower in the open plan living room and kitchen; however the maximum recommended level of 1,000ppm was exceeded in five out of the six dwellings monitored. Carbon dioxide in household No.3 did not exceed this level; however significantly lower occupancy rates were recorded during the measurement period. All average values of carbon dioxide remained below 1,000ppm.

Table 4. Summer carbon dioxide levels (ppm) in main bedroom

	No.1	No.2	No.3	No.4	No.5	No.6
Maximum	1453	1402	687.0	886	752.0	826
Minimum	455	440	436.0	467	412.0	410
Standard deviation	315.6	258.9	78.1	136.2	68.4	124.4
Average	875.5	831.2	546.9	662.9	501.6	596.3
Bedroom door status at night	Closed	Closed	Opened	Open	Opened	Closed
Bedroom window status at night	Closed	Closed	Closed	Closed	Opened	Opened
Night time occupancy	2 adults	2 adults, 1 child	1 adult	1 child	2 adults	2 adults

In the main bedroom, the recommended level of 1,000ppm was exceeded in two dwellings (No.1 and No.2) during the monitoring period. Occupants of these homes stated that the bedroom door and window were closed at night during the monitoring period, which may have contributed to the higher readings. All average levels of carbon dioxide were below 1,000ppm.

4.3. Relative humidity

4.3.1. Winter season

Table 5. Winter relative humidity (%)in living room and presence of mould

	No.1		No.2		No.3		No.4		No.5		No.6	
	Living room	Outside	Living room	Outside	Living room	Outside	Living room	Outside	Living room	Outside	Living room	Outside
Max	59.2	75	64.0	86.0	67.9	82	45.3	87	50.4	86	63.0	77
Min	51.4	60	49.4	77.0	56.7	65	36.4	77	37.8	67	35.7	39
SD	1.4	3.8	3.4	1.9	1.7	5.4	1.7	2.3	1.7	3.6	4.6	8.4
Mean	54.8	66.2	52.2	83.5	60.4	75	40.4	83.7	41.5	75.5	52.8	68.8
Mould	✓		×		✓		×		×		✓	

Values of relative humidity above 60% were recorded indoors in No.2, No.3 and No.6. In house No.3, the average relative humidity was 60.4%. This corresponds with the results from the occupant interview, as the three homes with the highest average relative humidity all reported the presence of mould within the last twelve months. Given that the homes are only two years old, the presence of mould in half is an alarming statistic. The worst affected areas are in the back bedrooms and bathrooms.

Fungal species require sufficient moisture, typically >60% relative humidity and adequate warmth for hyphal growth and spore germination (Crook et al. 2010). As explained by Crook and Burton (2010), emphasis on airtight building design for energy conservation purposes increases the potential for moisture and dampness problems, thus promoting the growth of mould. This is supported by the World Health Organization (2009), who explain that inadequately implemented energy efficiency measures such as increased airtightness, ventilation deficiencies and/or unsuitable insulation are linked to increased exposure to mould in residential buildings.

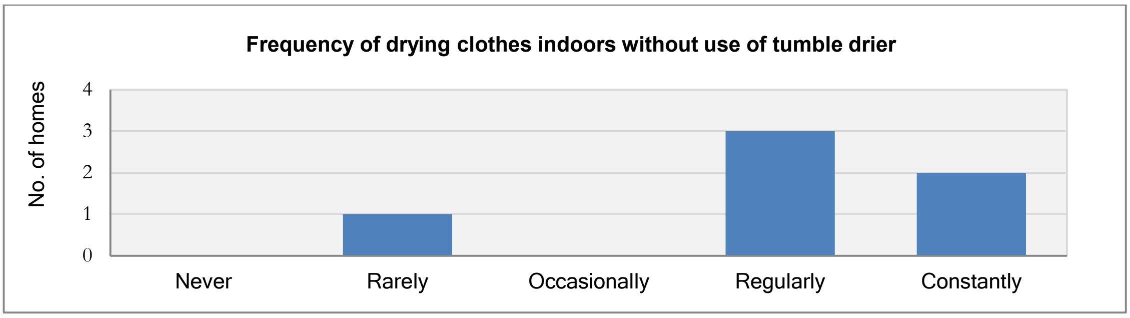

Figure 4. Household frequency of drying clothes indoors without the use of a tumble drier (winter)

During the interview process, households were asked if clothes are ever dried indoors without the use of a tumble drier; every home stated yes. Figure 4 shows the frequency of drying clothes indoors, with 5 out of 6 homes regularly or constantly using this method during the winter months. Only house No.5 reported rarely drying clothes indoors passively. This supports a UK study by Menon & Porteous (2012), who found 87% of respondents used passive indoor drying techniques during the heating season, rising to 96% in the spring. Furthermore, they found an average spore count of 1,398 CFU/m^3 in nine case study homes where passive indoor drying was used exclusively, compared to average spore count of 644 CFU/m^3 where a tumble drier was used either exclusively or predominantly. This suggests passively drying clothes indoors may promote mould growth, and thus ventilation design strategies should be capable of managing this.

4.3.2. Summer season

Table 6. Summer relative humidity (%) in living room (L), bedroom (B) and outside (O)

	No.1			No.2			No.3			No.4			No.5			No.6		
	L	B	O	L	B	O	L	B	O	L	B	O	L	B	O	L	B	O
Max	59.5	61.8	92.0	60.4	57.0	74.6	67.3	61.6	85.5	54.7	49.9	87.0	60.9	55.9	80.9	60.4	53.6	78.7
Min	50.4	47.2	60.0	41.6	35.2	38.4	58.5	54.8	57.6	35.3	40.5	48.0	48.8	44.2	57.1	44.3	37.6	45.0
SD	2.7	2.3	5.4	3.2	6.4	11.0	2.8	1.0	8.7	4.1	2.8	9.9	2.7	1.4	7.7	3.7	5.1	10.3
Mean	53.2	51.1	79.7	51.4	50.2	61.5	61.9	57.8	77.1	45.6	45.1	77.6	52.8	46.7	70.7	50.0	45.9	65.4

During the summer season, the maximum recommended level of 60% was exceeded in five out of six homes monitored, with average relative humidity levels exceeding 60% in the living room of one dwelling (No.3). Outside levels during the monitoring period did not appear to influence the results.

4.4. Temperature

4.4.1. Winter season

Table 7 shows the temperature results both indoors and outdoors during the measurement period. During this time, the occupants were asked to record periods when heating was used, either through use of gas/electric fire or portable electric heaters since no central heating system was available. Furthermore, during the interviews households were asked to record their typical heating schedule for each season and typical home occupancy levels, as illustrated in Table 8.

Table 7. Winter temperature results (° C) in living room and outside

	No.1		No.2		No.3		No.4		No.5		No.6	
	Living room	Outside	Living room	Outside	Living room	Outside	Living room	Outside	Living room	Outside	Living room	Outside
Max	20.1	5.7	23.3	8.8	22.4	8.6	23.4	9.4	25.4	8.7	23.6	15.4
Min	16.7	2.5	18.3	5.9	19.5	3.2	19.9	6.1	20.1	4.9	18.4	1.0
SD	1.0	0.8	1.4	0.7	0.7	1.5	0.8	1.0	1.2	0.9	1.4	3.4
Mean	18.0	3.5	20.5	6.7	20.8	5.3	21.3	7.1	21.3	6.2	20.2	4.9

Throughout the winter measurement period, the living room/kitchen of house No.1, 3, 4 and 5 was heated for approximately 2 hours, compared to house No.2 at 5 hours and house No.6 at 1 hour. During the summer, heating was used in only one home for approximately one hour (No.1). The temperature results do not correspond with these findings, therefore it is suggested indirect sources of heat (such as cooking or occupancy) or sources of heat loss may have influenced indoor temperature.

The heating schedules for all six homes vary considerably. According to the interview findings, the homes with the longest weekday and weekend occupancy also have the highest heating demand. Heating demands of 6-7 hours during the winter season were reported in three homes. Since no central heating is available, electric/gas fires or electric heaters are used to meet this demand, which may have a significant effect on electric and/or gas bills for each household. However this may be offset by the fact that almost all households reported using no form of heating during the summer months.

Households were also asked if they have ever experienced any problems with overheating in the home; four out of six answered yes (No.3, No.4, No.5 and No.6). Two explained problems with overheating occur sometimes when cooking and two stated they found problems with overheating at night during the summer time. In one household, occupants explained they tend to keep the windows open at night during summer as a result, however expressed issues with noise from opening the windows at night.

Table 8. Heating schedule and household occupancy

	No.1	No.2	No.3	No.4	No.5	No.6
Heating schedule during winter measurement period	(2 hours) 8-9pm, 5-6pm	(5 hours) 6-8pm, 8-10am, 12-1pm	(2 hours) 7-8am, 4-5pm	(2 hours) 7-9am	(2 hours) 2-4pm	(1 hour) 5-6pm

Heating schedule during summer measurement period	8-9am	-------	-------	-------	-------	-------
Reported heating schedule during spring (in home)	(2 hours) 7-9pm	(4 hours) 9-11am, 6-8pm	(4 hours) 7-8am, 9-10am, 6-8pm	(3.5 hours) 7-9am, 5.30-7pm	(2 hours) 8-10pm	(1 hour) 7-8pm
Reported heating schedule during summer (in home)	(1 hour) 9-10pm	-------	-------	-------	-------	-------
Reported heating schedule during autumn (in home)	(3 hours) 7-10pm	(4 hours) 9-11am, 6-8pm	(4 hours) 7-8am, 9-10am, 6-8pm	(3.5 hours) 7-9am, 5.30-7pm	(2 hours) 6-7am, 8-9pm	(2 hours) 7-9pm
Reported heating schedule during winter (in home)	(3 hours) 7-10pm	(7 hours) 9-12pm, 5-9pm	(6 hours) 7-10am, 6-9pm	(6 hours) 7-9am, 5-7pm, 9-11pm	(3 hours) 6-7am, 8-10pm	(4 hours) 12-2pm, 7-9pm
Average no. of hours home occupied during weekdays	17 hours	24 hours	24 hours	16 hours	12 hours	18-20 hours
Average no. of hours home occupied at weekend	20 hours	24 hours	24 hours	12-14 hours	12 hours	24 hours

4.4.2. Summer season

Table 9. Summer temperature (°C) in living room (L), bedroom (B) and outside (O)

	No.1			No.2			No.3			No.4			No.5			No.6		
	L	B	O	L	B	O	L	B	O	L	B	O	L	B	O	L	B	O
Max	24.0	22.4	17.9	25.7	27.6	26.2	23.8	23.8	21.7	23.2	22.9	18.4	28.2	25.2	21.8	25.4	23.6	21.6
Min	22.0	21.0	12.6	23.7	23.1	13.0	22.8	22.7	16.6	21.8	22.1	8.9	23.6	23.9	16.2	23.2	22.1	12.3
SD	0.4	0.4	1.7	0.6	1.2	2.6	0.2	0.3	1.7	0.4	0.2	2.3	0.9	0.2	2.0	0.4	0.4	2.4
Mean	22.7	21.7	14.2	24.8	24.8	16.3	23.2	23.3	18.2	22.4	22.4	12.3	26.1	24.5	18.4	24.4	22.9	16.6

During the summer measurements, overheating was evident in two homes with peak temperatures of 27.6°C in the bedroom of No.2 and 28.2°C in the living room of No.5. Average temperatures in the living room of three out of five dwellings were higher than recommended levels for comfort (18-24°C).

4.5. Formaldehyde levels in summer

Levels of formaldehyde peaked above the recommended limit of 0.08ppm in three of the six households monitored during the summer months. Significantly high average levels of 0.23ppm and 0.21ppm were recorded in No.1 and No.6. The data obtained from the occupant diary does not provide a reasonable explanation for these high levels. Figure 5 presents the levels of formaldehyde in No.1 over the 24 hour monitoring period.

Table 10. Summer formaldehyde levels (ppm) in living room

	No.1	No.2	No.3	No.4	No.5	No.6
Maximum	0.76	0.38	0.03	0.06	0.06	0.88
Minimum	0.04	0.00	0.00	0.00	0.00	0.00
Standard deviation	0.14	0.05	0.00	0.01	0.01	0.19

Average	0.23	0.02	0.00	0.00	0.00	0.21
Use of air fresheners	No	No	No	Yes	Yes	Yes
Use of scented candles or incense	No	No	No	Yes	Yes	No
Smoking indoors	No	No	No	Yes	No	No
Drying clothes naturally indoors	No	No	Yes	Yes	Yes	No

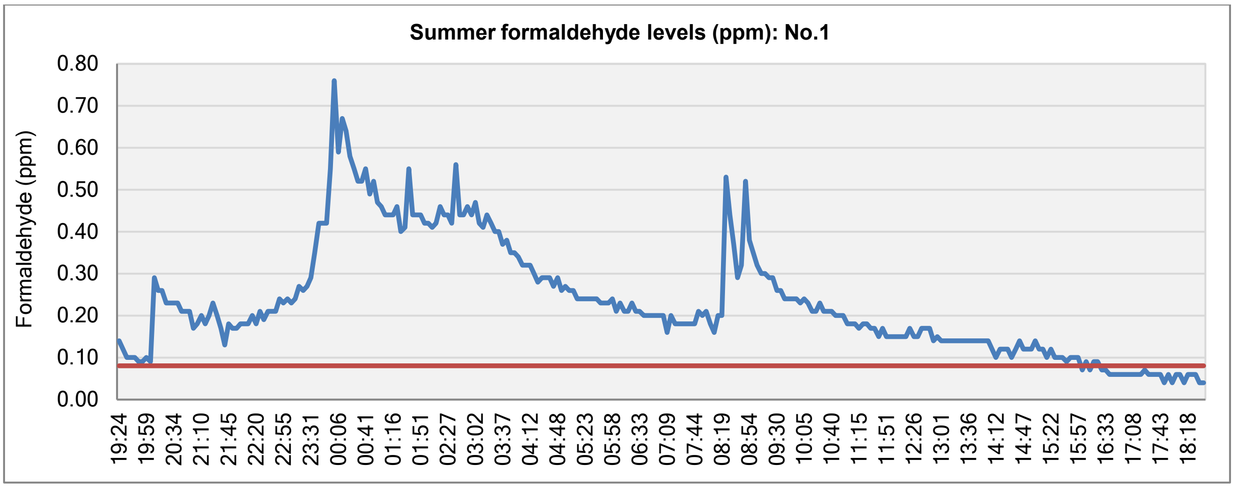

Figure 5. Summer formaldehyde levels in No.1

4.6. Occupant perception of the interior environment

Table 11. Perceived thermal comfort (all households)*

Thermal quality factors	Mean	SD	Mean +SD	Mean -SD	Max	Min
WINTER						
Comfortable(1)- uncomfortable(7)	3.5	1.2	4.8	2.3	6	2
Too hot(1) -too cold(7)	4.4	1.1	5.5	3.2	6	2
Satisfactory overall(1) -unsatisfactory overall(7)	3.7	1.2	4.9	2.5	6	2
SUMMER						
Comfortable(1) -uncomfortable(7)	2.8	1.5	4.4	1.3	6	1
Too hot(1) -too cold(7)	3.3	0.8	4.1	2.5	4	2
Satisfactory overall(1) -unsatisfactory overall(7)	2.5	1.0	3.5	1.4	4	1

*Occupants were asked to rate thermal comfort factors on a scale of 1-7 (for instance comfortable=1, uncomfortable=7)

Occupants were asked to rate various aspects of the interior thermal environment, which are presented in Table 8. Scales ranged from bi-polar to uni-polar depending on the variable. As suggested by Raw (1995), for uni-polar scales (where-by one extreme is bad and the other good), a score greater than 3 requires further investigation and a score greater than 5 is cause for concern. However for bi-polar scales (where-by neither extreme is ideal), a score outside the range of 3-5 requires further investigation and a score outside the range of 2-6 is cause for concern.

As illustrated in Table 11, the average value for the 'comfortable to uncomfortable' rating scale in winter was 3.5, suggesting occupants did not perceive the thermal environment as significantly comfortable. This is similar to the average score for 'satisfactory to unsatisfactory' rating scale of 3.7, suggesting the homes are not significantly satisfactory in winter. The average score for rating scale 'too hot-too cold' was 4.4, which suggests there was no significant problems with temperature during winter. It should be noted however that a maximum score of 6 and minimum score of 2 were recorded, which suggests significant variations in perceived thermal comfort.

Table 12. Perceived air quality (all households)*

Indoor air quality factors	Mean	SD	Mean +SD	Mean -SD	Max	Min
WINTER						
Dry(1)- humid(7)	4.0	0.6	4.6	3.4	5	3
Fresh(1)- stuffy(7)	3.6	0.8	4.4	2.8	5	2
Odorless(1)- odorous(7)	4.1	1.1	5.2	3.0	6	3
Too still(1) –too draughty(7)	3.5	0.9	4.5	2.6	5	2
Satisfactory overall(1)- unsatisfactory overall(7)	3.5	1.4	4.8	2.1	5	1
SUMMER						
Dry(1)- humid(7)	3.9	1.5	5.4	2.4	7	2
Fresh(1)- stuffy(7)	3.4	1.1	4.5	2.2	6	2
Odorless(1)- odorous(7)	3.3	1.3	4.5	2.0	6	2
Too still(1)- too draughty(7)	3.3	0.8	4.1	2.5	4	2
Satisfactory overall(1)- unsatisfactory overall(7)	2.6	1.1	3.8	1.5	4	1

*Occupants were asked to rate indoor air quality factors on a scale of 1-7 (for instance dry=1, humid=7)

The results for summer suggest much higher levels of comfort (average score of 2.8) and satisfaction of the thermal environment (average score 2.5). It should be noted however that maximum score for comfort levels was recorded as 6, again suggesting significant variations. The mean score for 'too hot-too cold' rating scale was 3.3 in summer, suggesting no significant problems with perceived temperature.

Occupants were also asked to rate the air quality both in summer and winter months. As shown in Table 12, various scales were utilized to describe the quality of the air. For the rating scale 'dry-humid' in winter, the average score was 4 which as suggested by Raw (1995) is an ideal score for a bi-polar scale. Both maximum and minimum scores suggest convergence in occupant's responses. Furthermore, an average score of 3.5 for rating scale 'too still-too draughty' in winter suggests no significant problems with air movement, however divergence in results was observed with maximum scores of 5 and minimum scores of 2 recorded.

However when asked to rate the air based on 'fresh-stuffy' rating scale in winter, the average score was 3.6 suggesting a problem with perceived freshness of air. This is supported by the results of the rating scale 'odorless-odorous' which scored an average value of 4.1 in winter, suggesting problems with odors. The average score for rating scale 'satisfactory overall-unsatisfactory overall' in winter of 3.5 suggests further investigation is required.

In comparison, the perceived air quality during the summer months was much better, with average value of 2.6 for rating scale 'satisfactory overall- unsatisfactory overall'. No significant problems were identified with rating scales 'dry-humid' (average score of 3.9) and 'too still-too draughty' (average score of 3.3). However, for rating scale 'fresh-stuffy', the average score was 3.4 suggesting the need for further investigation. This is similar to the average score for rating scale 'odorless-odorous' of 3.3.

Thus the results of air quality perception in the case study homes suggest further investigation is required for both summer and winter months, particularly in relation to perceived freshness of the air and perceived odors. Overall satisfaction of air quality in the homes was much better in summer months compared to winter months. One occupant explained this was due to the fact that during the summer months the windows could be opened for fresh air. This suggests that MVHR alone may not be sufficient in providing adequate perceived air quality in energy efficient homes.

4.7. Sick Building Syndrome symptoms

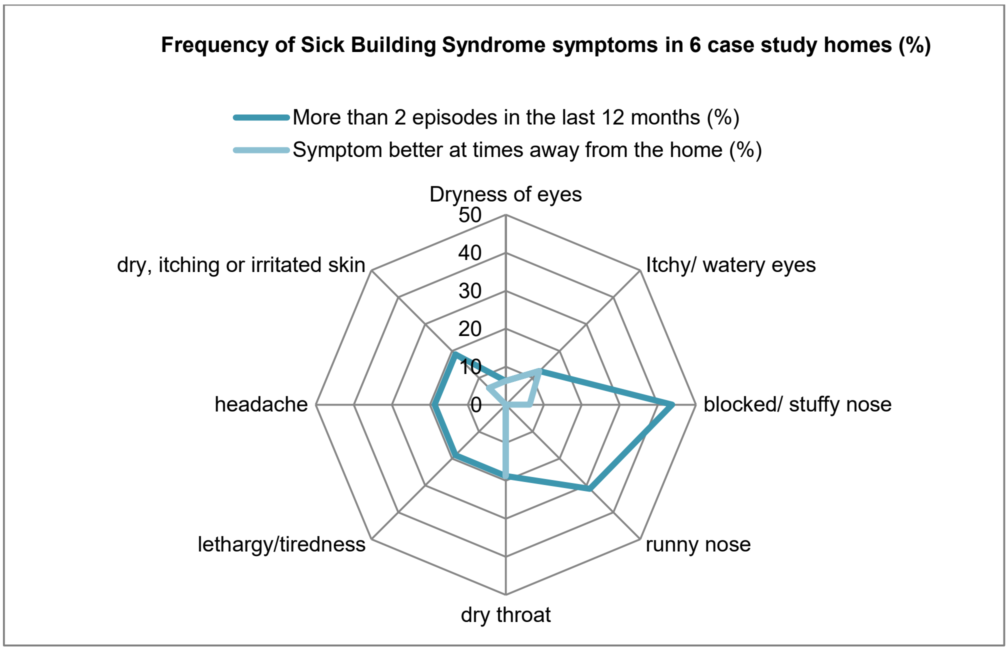

Figure 6. Frequency of Sick Building Syndrome (SBS) symptoms (percentage) experienced by building occupants

The frequency of Sick Building Syndrome (SBS) symptoms in the case study homes was investigated. Figure 6 presents the results. As illustrated, 44% of occupants reported experiencing more than two episodes of blocked/stuffy nose in the last 12 months, however only 6% stated that this symptom was better at times away from the home. Similarly, 31% reported experiencing more than two episodes of runny nose in the last twelve months, with none declaring the symptom to be better away from the home.

The most prevalent building related SBS among occupants of the six case study homes was 'dry throat', with 19% stating the symptom was better at times away from the home. Itchy/watery eyes was experienced by 13% of occupants more than twice in the last twelve months, all of whom stated the symptom was better at times away from the home. As explained by Murphy (2006), a 'sick building' is typically declared when over 20% of building occupants report symptoms (derived from the ASHRAE definition of acceptable indoor air quality).

As presented in Table 13, four out of six of the case study homes did not report any building related SBS symptom. However, in house No.3 and No.5, all occupants interviewed experienced more than two episodes of a SBS symptom in the last twelve months, which was better at times away from the home. Due to the small number of occupants in these homes it is difficult to declare the homes as 'sick' based on the 'more than 20% of occupants experiencing symptoms' rule of thumb. As stated by ASHRAE Standard 62-1989, "the air can be considered acceptably free of annoying contaminants if 80% of a panel of at least 20 untrained observers deems the air to be not objectionable under representative conditions of use and occupation". Since the definition of 'sick building' was derived from this standard, it is not particularly suitable for domestic environments.

Table 13. Building and Personal Symptom Index

House No.	BSI_8	BSI_5	Occupant	PSI_8	PSI_5
No.1	0	0	Adult (F)	0	0
			Adult (M)	0	0
			Child (F)	0	0
No.2	0	0	Adult (F)	0	0
			Adult (M)	0	0
No.3	1.67	1	Adult (F)	1	1
			Adult (M)	2	1
			Child (M)	2	1
No.4	0	0	Adult (F)	0	0
			Child (M)	0	0
			Child (M)	0	0
No.5	3	2	Adult (M)	3	2
No.6	0	0	Adult (F)	0	0
			Adult (F)	0	0
			Adult (M)	0	0
			Child (F)	0	0

The Building Symptom Index (BSI_5 and BSI_8) and Personal Symptom Index (PSI_5 and PSI_8) were calculated for each dwelling and respondent. As illustrated in Table 13, house No.3 scored a BSI_5 (5 symptoms: dryness of eyes, blocked/stuffy nose, dry throat, lethargy/tiredness and headache) of 1 while No.5 scored a BSI_5 of 2. Thus further investigation is required in these homes to identify the cause of these symptoms and whether or not it is related to the interior environment.

5. Discussion

The findings from the occupant interview suggest inadequate use of purge ventilation, in the form of opening windows or making use of the boost mode in the MVHR system. Problems with noise appears to be a significant factor, such as the noise of the MVHR system on higher settings or noise from outdoors experienced when windows are opened at night for thermal comfort. Furthermore, there appears to be a reluctance to engage with the MVHR system, with occupants explaining that they found the system easy to operate as it is automatic, and therefore they do not touch it. This may cause problems in future when maintenance is required, such as replacing filters or cleaning vents.

In some cases, occupants had adjusted supply vents for thermal comfort, explaining the vents were causing draughts. This is a significant problem, as it may result in air change rates below recommended levels for occupant health. Furthermore, another household described poor mixing of air, stating that downstairs may get too hot but at the same time upstairs can be too cold. The lack of a central heating system and reliance on secondary heaters in the main living space (gas/electric heater) and in the bedroom/s (electric heaters) results in localized heat; which in combination with inadequate ventilation may explain issues with mould growth in north facing bedroom/s and/or bathroom.

Recorded carbon dioxide levels during winter suggest inadequate ventilation in 5 out of 6 of the case study homes, with maximum values over 2,000ppm in half of case study dwellings. In summer, five out of six households recorded carbon dioxide levels above recommended limits in the open plan living area and two households in the bedroom. Carbon dioxide levels were lower during the summer monitoring period, most likely due to increased purge ventilation from opening windows. The high levels of carbon dioxide observed may be due to poor commissioning of the ventilation system, occupant interference with vents, inadequate use of purge ventilation and/or system faults. It is recommended therefore if installing MVHR, the system should be installed with a silencer to keep noise to a minimum. Furthermore, supply and extract vents should be fitted in a way to avoid occupant interference after commissioning, in order to ensure adequate ventilation. Occupants should be briefed on how to effectively utilize the ventilation system, including use of the boost mode. Carbon dioxide sensors should be utilized to automatically increase ventilation rates when levels rise above that recommended.

Moisture control is an important factor to consider in the design of energy efficient buildings since they present greater potential for problems. In particular, provision for drying clothes in a way that does not contribute to excessive indoor moisture (or excessive energy use) is a significant issue facing the design community. For instance, the indoor air quality measurements identified high relative humidities (over 60%) in half of the case study homes during winter and five out of six dwellings monitored during summer. Furthermore, the interview process identified mould growth in 3 out of 6 homes. More research is required to identify the extent of fungal growth in energy efficient homes, including the spore counts and the identification of fungal species present in these environments.

Average indoor temperatures in the six homes ranged from 18-22 ºC during the 24 hour winter measurement period. Indoor temperatures did not correspond significantly with heating patterns, however in most cases heating devices were only used for 1-2 hours during this time. During winter months half of households stated heating demands of 6-7 hours a day, which was met by secondary heating devices (such as gas/electric fire). Overheating was experienced by occupants in four out of six homes, which suggests problems with ventilation. This corresponds with the results of the summer measurements, where peak temperatures of 27.6 °C were recorded in No.2 (bedroom) and 28.2 °C in No.5 (open plan living room). Average temperatures were higher than the recommended levels for comfort (18-24°C) in three out of six monitored homes. This suggests significant internal sources of heat and/or inadequate ventilation in the case study dwellings. Thus more attention to overheating in new build dwellings may be required to ensure adequate indoor air quality during summer months.

Occupants were asked at the end of the interview if there were any aspects of the building design that could be improved in order to achieve better indoor air quality. In two of the homes occupants suggested the windows could be improved or could be more airtight. One home suggested an improvement of the heat recovery aspect of the mechanical ventilation system in winter to alleviate cold draughts. Furthermore, one household suggested problems with circulation of heat, proposing that the stairs could be opened up to allow hot air to circulate upstairs. Thus it could be suggested that the majority of complaints/suggested improvements are related to the thermal environment. This does not reflect the physical measurements, which found average temperatures within a comfortable range during the 24 hour winter measurement period despite limited use of heating devices in the majority of homes.

Results on perception of the indoor environment suggest occupants did not find the homes significantly comfortable or satisfactory during the winter months. Furthermore, issues with satisfaction of the indoor air quality were identified, including problems with perceived freshness of air and odors in winter. Perception of thermal comfort and indoor air quality was much better for summer months; however significant variations of responses exist. One occupant explained the ability to open windows for fresh air during summer improved perception of air quality. This suggests the need for hybrid responses to ventilation design incorporating both mechanical and natural strategies.

The presence of building related Sick Building Syndrome (SBS) symptoms in two case study homes (No.3 and No.5) suggest the need for further investigation to identify the cause. The most prevalent building related symptom was dry throat (19%), followed by itchy/watery eyes (13%). In house No.3, one occupant explained the prevalence of 'dry throat' was worse during the morning time, and suggested the use of the electric heater in the bedroom could be the cause. The prevalence of 'dry throat' for another occupant of house No.3 was worse in winter, particularly on rainy days. The occupant explained the symptom may be related to mould growing on furniture in the bedroom. Further investigation in these homes, including identification of ventilation effectiveness and sampling of fungal spores will provide important information to help establish causal factors for these symptoms.

Over-all, the objective and subjective measurements of thermal comfort present divergence of results. Throughout the measurement period, all homes remained within comfortable levels. However, findings from the interviews suggest occupants did not find the homes significantly comfortable or satisfactory during the winter months. This may be as a result of higher expectations of comfort in energy efficient homes or possibly lower perception of thermal comfort due to the omission of a central heating system. Since only the main living space and bedroom was monitored, temperature fluctuations may exist in other areas of the building. As some occupants pointed out, upstairs was perceived to be much colder than downstairs. Thus further monitoring may be useful to identify temperature variations between different rooms in the homes.

In contrast, the objective and subjective measurements of indoor air quality suggest a degree of convergence in results. For instance, perceived indoor air quality suggests problems with freshness of air and odors, which is supported by the high levels of carbon dioxide observed during the measurement periods. The presence of mould is supported by high levels of relative humidity in three of the case study homes during winter and five homes during summer. Furthermore, the presence of SBS symptoms in two of the case study homes suggests problems with indoor air quality. The cause of these symptoms however is not clear, thus further investigation may be required.

The case study homes are compliant with Code for Sustainable Home's level 4, with energy aspects equivalent to level 5. The Code for Sustainable homes provides a step change to meet zero carbon by 2016, thus will "form the basis for future developments of the Building Regulations in relation to carbon emissions from, and energy use in homes" (Department of Communities and Local Government, 2006). The findings from this study suggest the Code for Sustainable Homes rating system does not adequately satisfy indoor air quality requirements. In fact, the code does not directly address any issue regarding indoor air quality. This is particularly alarming and suggests the need for significant improvements to the assessment tool in order to ensure the protection of occupant health in low energy dwellings.

5. Conclusions

This study investigated the indoor air quality of energy efficient case study homes in the UK during the winter and summer months. The results of the sampling suggest high levels of carbon dioxide, relative humidity, formaldehyde and summer time temperatures. Occupant interviews found concerns with perceived indoor air quality and thermal comfort, occupant engagement with the ventilation system, the use of purge ventilation, prevalence of drying clothes indoors, presence of sick building syndrome symptoms and issues with overheating. Further research is required to identify the extent of this problem in energy efficient homes in the UK, since data of this kind is essentially lacking.

The case study dwellings are considered an innovative example of energy efficient building design. While these homes substantially reduce energy demand and carbon emissions, there is still significant research required to ensure indoor air quality is not sacrificed as a result. It is hoped that this information may be used to aid the design of effective sustainable residential buildings that consider not only energy efficiency, but also adequately address occupant health and exposure to indoor air pollutants.

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